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Technical Note

PX—An Innovative Safety Concept for an Unmanned Reactor

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ABSTRACT

An innovative safety concept for a light water reactor has been developed at the Korea Atomic Energy Research Institute. It is a unique concept that adopts both a fast heat transfer mechanism for a small containment and a changing mechanism of the cooling geometry to take advantage of the potential, thermal, and dynamic energies of the cold water in the containment. It can bring about rapid cooling of the containment and long-term cooling of the decay heat. By virtue of this innovative concept, nuclear fuel damage events can be prevented. The ultimate heat transfer mechanism contributes to minimization of the heat exchanger size and containment volume. A small containment can ensure the underground construction, which can use river or seawater as an ultimate heat sink. The changing mechanism of the cooling geometry simplifies several safety systems and unifies diverse functions. Simplicity of the present safety system does not require any operator actions during events or accidents. Therefore, the unique safety concept of PX can realize both economic competitiveness and inherent safety.

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1. Introduction

A simple safety system is one of the major design features that can assure the inherent safety and passive operation of a nuclear power plant. In light of the Fukushima Daiichi nuclear accident, the need for simpler safety systems has become more pressing. This will call for radical design concepts that can eliminate human error and miscommunications more effectively. Furthermore, an ultimate passive cooling mechanism should be considered to prevent severe accidents, as well as beyond-design-basis accidents in a station blackout scenario. Recently, the newly developed

design concepts of both large-sized conventional light water reactors of an European Simplified Boiling Water Reactor (ESBWR) and Advanced Plant 1000 MWe (AP1000), and small- and medium-sized reactors of mPower, Modular Scalable Nuclear Power (NuScale), and System-Integrated Modular Reactor (SMART) [1,2] have aimed to enhance both inherent safety and competitive economics. However, it is not easy to resolve both contradictory needs at the same time. Most safety systems of currently operating light water reactors have a large containment, additional tanks, and complex piping systems compared to the volume of the reactor pressure vessel. In these reactors, typical systems for design-

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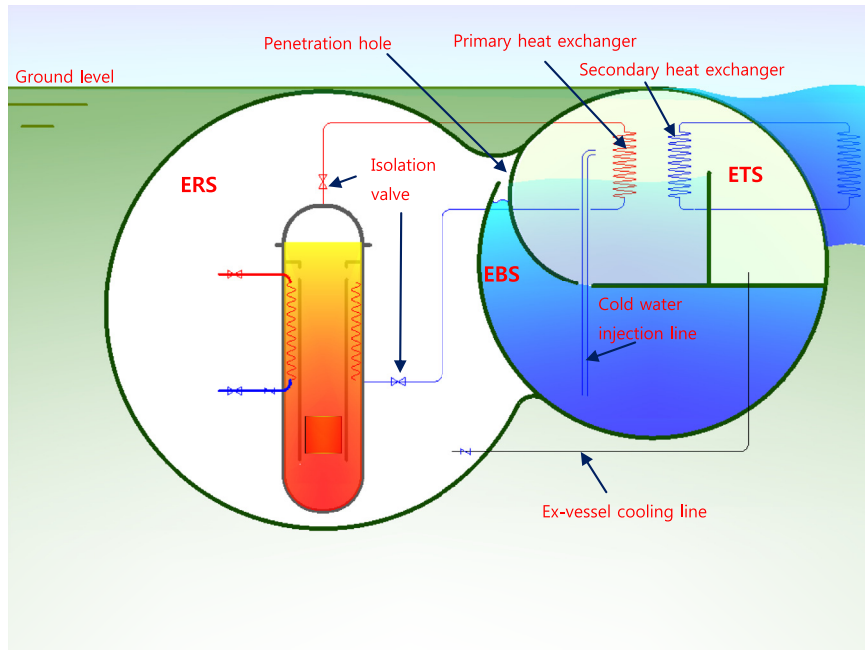


Fig. 1 – Schematic view of the innovative safety concept of PX. EBS, energy buffer space; ERS, energy release space; ETS, energy transfer space.

basis accidents are the safety injection system, residual heat removal system, depressurization system, and containment cooling system, and for a severe accident, the molten core cooling system. However, these diverse safety systems have not yet achieved the absolute safety, even though the structures and volumes become more complex and larger to contain these safety components. These systems can expose these reactors to other unexpected human errors and accidents that are linked to external hazards or the possibility of a pipe break. To find a successful path toward solving these problems, it is necessary to simplify the system and unify the diverse functions. This will provide a guarantee of absolute safety and passive operation. Therefore, in this paper, an innovative concept is introduced to enhance reactor safety.

2. Concept of PX

The conceptual geometry of PX has three volumes, i.e., an energy release space (ERS), energy buffer space (EBS), and energy transfer space (ETS) in twin containments, as shown in Fig. 1. The ERS is in the left containment, and both the ETS and the EBS are in the right containment, in the upper and lower parts, respectively. The reactor vessel, which is presumed to be a kind of integrated-type light water reactor, is in the left containment, and the primary heat exchanger, secondary heat exchanger, and injection spray line, which is connected to the EBS, are in the upper part of the right containment. The lower part of the right containment is a water reservoir, which is fully filled with cold water initially. The name PX originated from the P of peanut owing to the shape of the twin containments, and X, which indicates the shape of the flow pattern in

the twin containment during an accident. It has the following conceptual working sequences after reactor shutdown conditions: (1) There are three spaces of ERS, EBS, and ETS, respectively, for the release, buffer, and transfer of energy to cool down the residual heat of the core after a reactor shutdown. (2) The pressure of the ERS increases when the steam is discharged out of the reactor vessel, steam line, or feed water line during mass release accidents. (3) The cold water in the EBS is injected into the primary heat exchanger tubes of the ETS by virtue of the high pressure of the ERS. (4) The cold water injected cools down the primary heat exchanger and is evaporated on its surface. (5) The hot steam in the ETS is condensed on the surface of the secondary heat exchanger tubes. (6) The secondary heat exchanger transfers the energy in the ETS to a pool outside of the containment, which functions as an ultimate heat sink.

For the innovative safety system introduced in this paper, two key physical concepts are adopted in PX, i.e., the fast heat transfer mechanism in the ETS and the changing mechanism of the cooling geometry (CCG) between the three spaces of ERS, EBS, and ETS.

2.1. Fast heat transfer mechanism

To remove the heat out of the reactor into the atmosphere, a possible method of maximum heat transfer is two-phase spray jet quenching in the ETS, as shown in Fig. 2. A sprayed droplet is evaporated on the outer surface of the primary heat exchanger tube, and the steam is condensed inside the tube. At the same time, the vaporized hot steam in the ETS is condensed on the outer surface of the secondary heat exchanger tube, while the water inside is boiled.

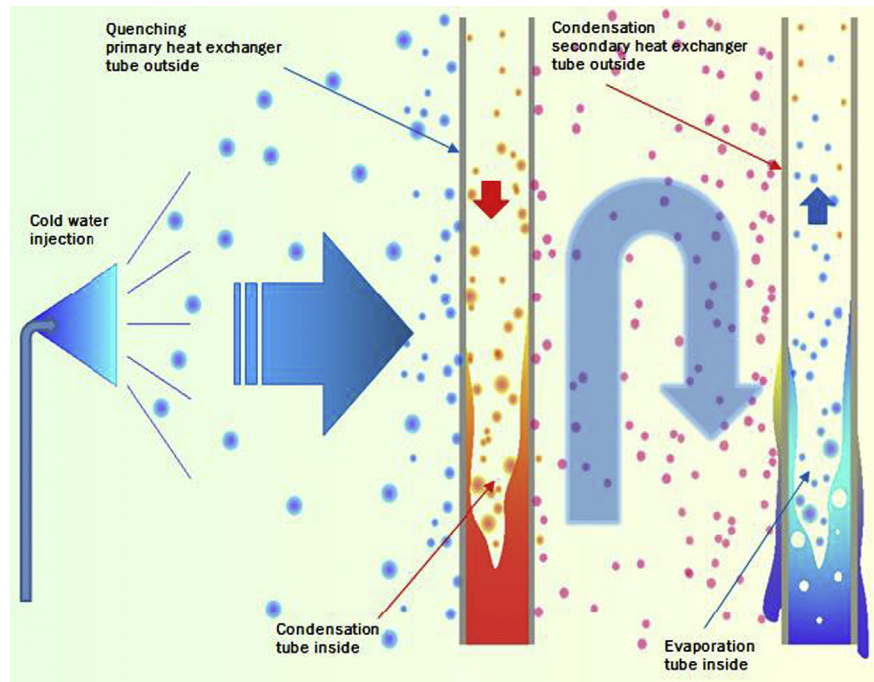


Fig. 2 – Two-phase heat transfer mechanism in ETS. ETS, energy transfer space.

Finally, the energy in the ETS is removed through an ultimate heat sink, such as seawater or an air cooler. The heat transfer rate, by virtue of this mechanism, is very fast, and sufficient to transfer the heat of the ERS into the atmosphere

without a bottleneck in heat transfer between the reactor and atmosphere. The order of magnitude for this heat transfer rate is above 10 times that of other methods, such as two-phase pool boiling [3–6]. This fast heat transfer

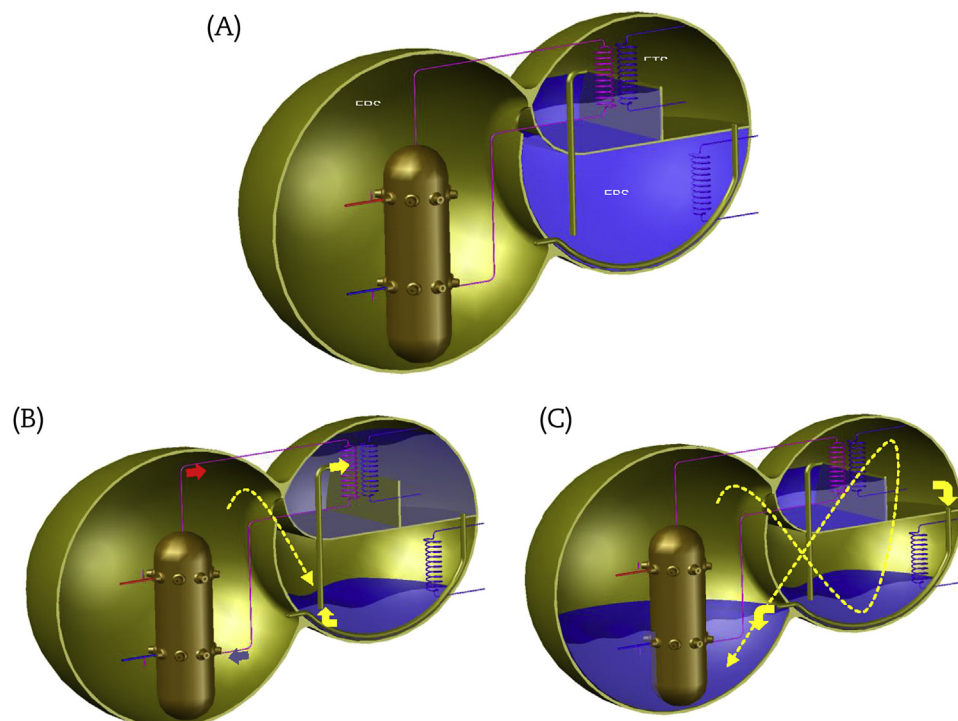


Fig. 3 – Sequential cooling mechanism of CCG concept. (A) Normal operation. (B) Fast cooling. (C) Long-term cooling. CCG, Change of Cooling Geometry; EBS, energy buffer space; ERS, energy release space; ETS, energy transfer space.

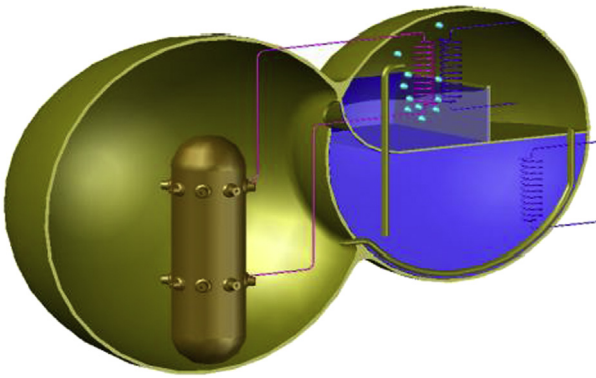


Fig. 4 – Cooling mechanism of COI without CCG. CCG, changing mechanism of the cooling geometry; COI, change of inventory status.

mechanism can reduce the sizes of both the containment and the heat exchanger, and no additional cooling system, such as a safety injection system or a containment cooling system, is required.

2.2. Changing mechanism of cooling geometry

- (1) The major systems of PX consist of a nuclear steam supply system, a primary heat exchanger, a secondary heat exchanger, and a cold water injection line in the

twin containments, and each of them has the following functions: (1) nuclear steam supply system: some kind of power source; (2) primary heat exchanger: circulation loop to remove the decay heat in the ERS; (3) secondary heat exchanger: circulation loop to cool down the ETS; (4) cold water injection line: pumping line of cold water from the EBS to the ETS.

To describe the detailed working concept of the CCG and fast cooling mechanism, the concept of a loss of inventory (LOI) accident was adopted. If a break on the pressure boundary occurs in the left containment, then the reactor is tripped, followed by the steam and feed water line isolation. The accident scenario has three phases: normal operation, fast cooling, and long-term cooling. Fig. 3 shows the sequential cooling mechanism of the CCG.

Fig. 3A shows the nominal reactor operation status. The ERS is filled with air and the ETS is also filled with air at the same pressure as the ERS, while the EBS is filled with cold water. Fig. 3B shows the fast cooling status during an accident transient after a break. In this phase, the cold water in the EBS is pumped up to the ETS for spray quenching of the primary heat exchanger. During this phase, most of the cold water in the EBS was moved to the ETS. Finally, if the pressures of the ERS and ETS become equal, then the water of the ETS will go down to the ERS due to gravity. Fig. 3C shows the final steady long-term cooling phase, which is accomplished by the steam generated in and discharged out of the ERS, its condensation in the ETS, and returning of the condensed water to the ERS.

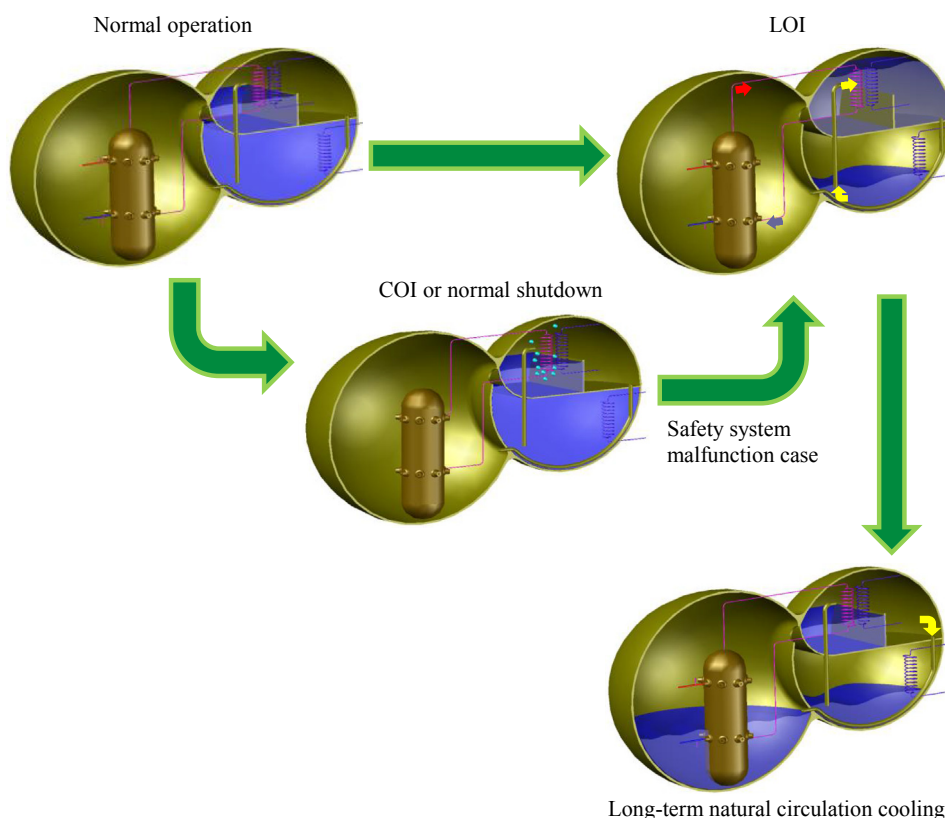


Fig. 5 – Overall concept of AM strategy for the accidents. AM, accident management; COI, change of inventory status; LOI, loss of inventory.

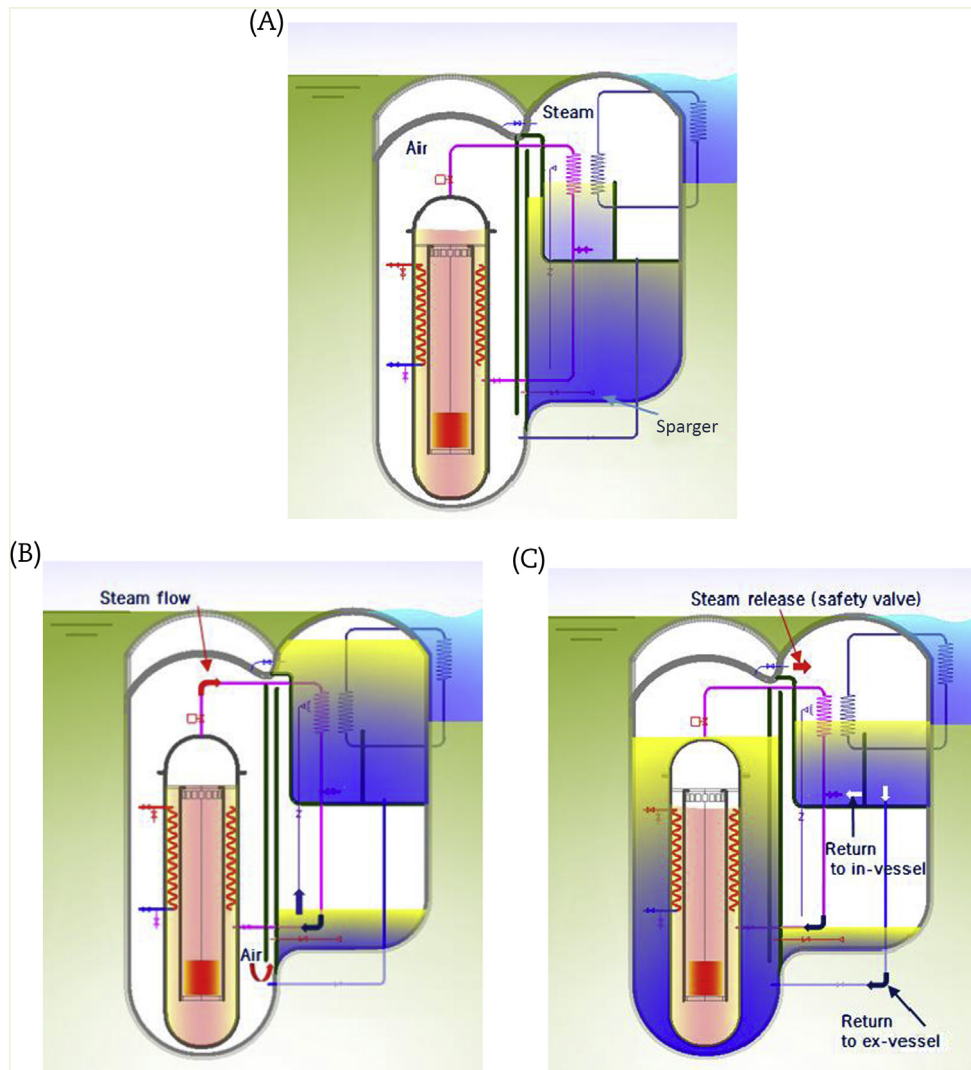


Fig. 6 – Feasible design and flow pattern of PX for LOI accidents. (A) Normal operation. (B) Fast cooling. (C) Long-term cooling. LOI, loss of inventory.

Therefore, the meaning of CCG used in this paper is derived from the coolant moving phenomena during the three phases of normal operation, fast cooling, and long-term cooling. This sequential flow pattern has an X shape in the twin containments.

3. New classification of accidents and sequence of events

The innovative safety concept developed in this work, called PX, requires a new accident management (AM) strategy due to its functional spaces in the twin containments. In the AM strategy for PX, all events and accidents need to be classified anew, unlike the current binary spectrum of a loss-of-coolant accident or non-loss-of-coolant accident. In PX,

most of the accidents can be classified into three types. The first one is LOI cases such as loss of coolant accidents, steam line break, and feed line break, which include mass and energy release out of the pressure boundary. The second one is change of inventory status cases such as a steam generator tube rupture) and total loss of flow. Here, the inventory status means inventory relocation between the primary reactor and secondary system, and momentum or energy change in the reactor coolant system. The third one is a core damage case resulting from a failure of the safety functions. The AM concepts used to mitigate these accidents are described for these three cases in the following: (1) LOI: AM function is initiated using high-pressure steam from the ERS, which finally moved to the long-term natural circulation mode, as described in Figs. 3A–3C, using the concept of CCG. (2) Change of inventory status: the reactor can be cooled down passively by the primary and secondary heat

exchangers, the lower parts of which are submerged in the pool of the ETS, as shown in Fig. 4. (3) Core damage: in the case of core damage, the decay heat from the core is cooled down by natural circulation between the twin containments, as shown in Fig. 3C.

Fig. 5 shows the overall AM strategy for the accidents. This self-diagnostic management strategy will make the operation very simple and also ensures unlimited core-cooling capability eventually.

4. Feasible design for PX

In order to realize the innovative concept of PX, a feasible design is suggested for the conceptual design. Fig. 6 shows a feasible design concept of PX. In this paper, an LOI accident is considered as a base accident scenario, as it is one of the most important accident scenarios that involve a fast cooling mechanism. The working processes in Fig. 6 correspond to those in Fig. 3. The design concept of PX is summarized briefly as follows: (1) underground location (a) to use ultimate heat sink (easy to use the water from sea or river); (b) small double and twin containments (for a measure against external disasters); (2) simple unified safety system (no safety injection and containment spray); (3) self-diagnosis for the accidents of LOI, change of inventory status, and core damage (CCG phenomenon depends on the pressure balance between the twin containments); (4) long-term cooling with natural circulation between the ERS and ETS.

The general working concept of a feasible system design was already mentioned in the description of the concept of PX in the second section. In the case of an LOI accident, the detailed sequences of events are described as follows. (1) At the beginning of a break accident in the ERS, the air in the ERS goes into the entrance of the upside-down manometer duct fabricated on the wall between the ERS and the EAS, and pushes the water in the EBS into the ETS. This water is injected onto the surface of the primary heat exchanger, as shown in Fig. 6B. (2) After a certain period, the reactor is tripped and the isolation valves are opened following the given conditions for reactor protection. After that, the high-temperature steam circulates between the reactor vessel and the primary heat exchanger. At the same time, a fast heat transfer occurs between the primary and secondary heat exchangers by virtue of a spray jet supplied from the EBS, as described in Fig. 2. (3) If the pressures of the left- and right-hand side containments become equal, the water in the upper part of the ETS goes down into the ERS due to gravity and cools down the outer surface of the reactor vessel in the ETS. (4) The reactor pressure decreases continuously. Finally, the pressure inside becomes equal to that outside, and another circulation flow then occurs due to the opening of the isolation valve installed on the primary heat exchanger, which is located in the lower part of the ETS. (5) The energy of the ETS is eliminated by the secondary heat exchanger during

an accident. (6) The binary natural circulation mode is the ultimate long-term cooling mechanism for preventing severe accidents. Therefore, this final safe cooling mode will be continued by virtue of an unlimited heat sink such as water from the sea or a river.

5. Discussion

A simple safety concept, PX, was developed at the Korea Atomic Energy Research Institute. This innovative concept has two unique characteristics. One is an ultimate heat transfer mechanism and the other is the CCG. Applying this concept, it is possible to make the containment size small and to achieve ultimate long-term cooling. Additionally, this simplified concept for a reactor safety system has the distinguished ability of self-diagnosis for most accidents. With some additional AM, unmanned reactor operation will be possible in the near future. Finally, this innovative concept will contribute to economic competitiveness and inherent safety, especially for small modular reactors.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

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